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Acoustical oceanography and satellite remote sensing

A report from the 140th Acoustical Society of America meeting

D. Hutt

Defence R&D Canada

Technical Memorandum
DRDC Atlantic TM 2003-263
December 2003

Canada

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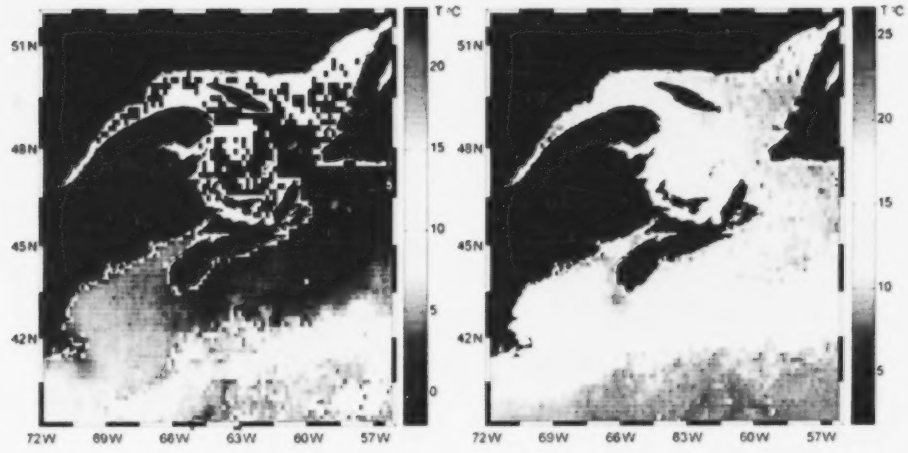

Defence R&D Canada – Atlantic

Technical Memorandum

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Author

D. L. Hutt

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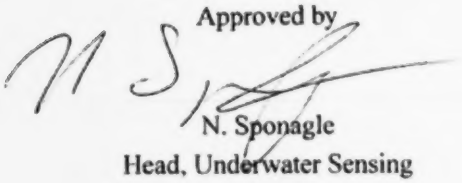

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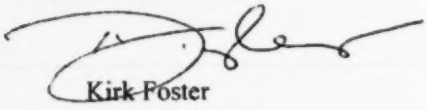

Kirk Foster
DRP Chair

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Abstract

Knowledge of underwater acoustical propagation conditions and the structure of the ambient noise field is required in order to predict the performance of naval acoustical systems. In recent years there has been increasing interest in exploiting data from remote sensing satellites to improve assessment of the underwater acoustical environment. Acoustical oceanography and satellite remote sensing was the theme of a special session of the Acoustical Society of America (ASA) meeting held at Newport Beach, California in December, 2000. The session brought together researchers in underwater acoustics, physical oceanography and remote sensing to examine the growing synergy between these three fields. This report presents highlights of the session and interpretation of research activities relevant to DRDC Atlantic and the Canadian Forces.

Résumé

La connaissance des conditions de propagation acoustique sous-marine et de la structure du champ sonore ambiant est pertinente, car elle permet de prédire le comportement de systèmes acoustiques de la marine. Depuis quelques années, on a noté un intérêt grandissant pour l'exploitation des données des satellites de télédétection pour raffiner l'évaluation de l'environnement acoustique sous-marin. L'océanographie acoustique et la télédétection par satellite constituaient le thème d'une séance spéciale du Congrès de l'Acoustical Society of America (ASA), tenu à Newport Beach (Californie), en décembre 2000. Au cours de cette séance, des chercheurs en acoustique sous-marine, en océanographie physique et en télédétection ont considéré la synergie grandissante entre ces trois domaines. Ce rapport présente les points saillants de cette séance qui pourront intéresser le RDDC Atlantique et les Forces Canadiens.

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Executive Summary

Background

At first glance underwater acoustics, satellite remote sensing and oceanographic modelling may seem to have little in common. However, in recent years it has become clear that assimilation of remotely sensed data into ocean models may significantly enhance predictions of the underwater acoustical environment. Knowledge of underwater acoustical propagation conditions and the structure of the ambient noise field is of interest to the military for performance prediction of acoustical systems as well as being of interest to oceanographers and environmentalists. Acoustical oceanography and satellite remote sensing was the theme of a special session of the Acoustical Society of America meeting held at Newport Beach, California in December, 2000. The session, chaired by the author, brought together researchers in underwater acoustics, physical oceanography and remote sensing to examine the growing synergy between these three fields.

Results

This report presents the highlights of the session which covered subjects ranging from techniques to assimilate remotely sensed data into oceanographic models to detection and modelling of internal waves. Of particular significance to the Canadian Force was work on ocean modelling of the Scotian Shelf and a review of the US Navy's operational global ocean data assimilation system, MODAS. Of direct relevance to sonar performance prediction was work presented on underwater acoustical propagation through internal waves and detection of internal waves using space-based synthetic aperture radar (SAR). Finally, work was presented on the use of remotely sensed surface wind fields and ship detections, both derived from satellite SAR imagery, to estimate underwater ambient noise. Taken together, these research efforts represent substantial progress in the estimation of underwater acoustical parameters with the aid of satellite remote sensing.

Hutt, Daniel L. 2003. Acoustical oceanography and satellite remote sensing: A report from the 140th Acoustical Society of America meeting. DRDC Atlantic TM 2003-263. Defence R&D Canada – Atlantic.

Sommaire

Context

À première vue, l'acoustique sous-marine, la télédétection par satellite et la modélisation océanographique ne semblent pas présenter beaucoup d'éléments en commun. Toutefois, depuis quelques années, il est devenu évident que l'inclusion de données de télédétection aux modèles des océans peut améliorer grandement les prévisions des conditions acoustiques de l'environnement sous-marin. La connaissance des conditions de propagation acoustique sous-marine et de la structure du champ sonore ambiant a suscité de l'intérêt chez les militaires, car elle permet de prédire le comportement de systèmes acoustiques, en plus d'intéresser les océanographes et les environnementalistes. L'océanographie acoustique et la télédétection par satellite constituaient le thème d'une séance spéciale du Congrès de l'Acoustical Society of America, tenu à Newport Beach (Californie), en décembre 2000. Au cours de cette séance, des chercheurs en acoustique sous-marine, en océanographie physique et en télédétection ont considéré la synergie grandissante entre ces trois domaines. Présidée par l'auteur, la séance a porté sur des sujets allant des techniques d'incorporation des données de télédétection aux modèles océanographiques, à la détection et à la modélisation des vagues internes. Ce rapport présente les points saillants de cette séance.

Résultats

Dans ce rapport on présente les faits saillants de la séance couvrant des sujets allant des techniques d'assimilation des données de télédétection dans des modèles océanographiques à la détection et la modélisation des ondes internes. Les travaux sur la modélisation océanique pour la plate-forme Néo-Écossaise et un examen par la marine américaine du système opérationnel d'assimilation de données océaniques mondiales (MODAS) présentaient un intérêt particulier pour les militaires canadiens. Les travaux sur la propagation acoustique sous-marine par les ondes internes et la détection des ondes internes au moyen de radars à synthèse d'ouverture (RSO) satelliportés présentaient un intérêt direct en rapport avec le fonctionnement du sonar. Enfin, on a présenté des travaux sur l'utilisation des champs de vent télédétectés et la détection des navires sur l'imagerie RSO satellite pour l'estimation du bruit sous-marin ambiant. Collectivement, ces efforts de recherche constituent un pas important vers l'estimation des paramètres acoustiques sous-marins à l'aide de la télédétection par satellite.

Hutt, Daniel L., 2003. Acoustical oceanography and satellite remote sensing: A report from the 140th Acoustical Society of America. [Océanographie acoustique et télédétection par satellite : Rapport du 140e Congrès de l'Acoustical Society of America]. RDDC Atlantique TM 2003-263. R et D pour la défense Canada - Atlantique.

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Thanks are also extended to keynote speakers; Josko Bobanovic, Dalhousie University, Charles Barron, Naval Research Laboratory, Stennis Space Center, Henrik Schmidt, Massachusetts Institute of Technology, Roger Gauss, Naval Research Laboratory, Washington DC and Justin Small, DERA Winfrith (now with University of Hawaii). All of the speakers provided input and graphical material used throughout this report.

Finally the author would like to thank Paris Vachon, Canada Centre for Remote Sensing for processing the RADARSAT-1 data that was used to create Figs. 4.2 and 5.2 to 5.4.

1. Introduction

At first glance underwater acoustics, satellite remote sensing and oceanographic modelling may seem to have little in common. However, in recent years it has become clear that assimilation of remotely sensed data into ocean models may significantly enhance predictions of the underwater acoustical environment. Knowledge of underwater acoustical propagation conditions and the structure of the ambient noise field is of interest to oceanographers, the military and environmentalists.

Acoustical oceanography and satellite remote sensing was the theme of a special session of the Acoustical Society of America (ASA) meeting held at Newport Beach, California in December, 2000. The session, chaired by the author, brought together researchers in underwater acoustics, physical oceanography and remote sensing to examine the growing synergy between these three fields.

Much of the material in this report was published in Backscatter magazine in 2001 (Ref. 1). This report is an expanded and updated version of Ref. 1 with emphasis placed on activities that are potentially of interest to the Canadian Forces (CF). In the maritime battle space, various oceanographic parameters can influence the performance of sensors, weapons, vessels and human operators. Operational knowledge of these parameters represents a substantive military advantage. Relevant parameters include water temperature, surface and subsurface currents, the presence of oceanic fronts and eddies, water turbidity, the presence of fluorescing organisms, sea state, sea bottom composition, beach conditions, water density, the presence of internal waves, and ice conditions.

Traditionally, *in situ* sensors have been the main tool for ocean environmental assessment. The CF obtains operational ocean data from *in situ* sensors deployed from aircraft, ships, submarines, free-floating buoys and fixed moorings. However, today operational oceanographic satellite sensors provide the capability to generate synoptic surveys of the maritime battle space on time scales of minutes to hours. *In situ* sensors and satellite sensors are complementary in that *in situ* sensors can provide accurate data on the entire water column at a fixed location while satellite sensors provide data over a wide area but are mostly limited to information about the sea surface.

The best way to exploit the benefits of both of these data sources is assimilate all available data into an ocean model which performs an interpolation between the spatial and temporal domains of the *in situ* and remotely sensed data and can also provide a predictive capability. Chapter 2 of this report is about work in ocean modelling to achieve these goals.

The subsequent chapters focus on exploitation of remote sensing of the sea surface to glean information on parameters that affect the underwater acoustical environment. Chapter 3 describes remote sensing of internal waves and their impact on sonar performance. Chapter 4 describes the potential for remote sensing to provide information of use in predicting sea surface acoustic scattering and absorption and Chapter 5 presents a concept for using remotely sensed winds and ship detections to estimate underwater ambient noise.

2. Oceanographic modelling and remote sensing

Work on ocean modelling was presented by several researchers, reflecting the large effort presently dedicated to this field in many countries. All of the work presented was funded by defence organizations which is in keeping with the fact that ocean models can provide valuable nowcasts and forecasts of water column quantities temperature, salinity and sound speed. The assimilation of remotely sensed data into ocean models to improve their performance is the area of research where the greatest gains are expected to be made in the next five to ten years. The surge in ocean modelling activity over the past ten years has been driven primarily by two technical developments; availability of high quality remotely sensed global ocean data and the rapid increase in available computational power.

2.1 High-resolution ocean model of Scotian Shelf

Joško Bobanovic (Dalhousie University, Canada) described estimation of water temperature and salinity structure with a high resolution ocean model of the Scotian Shelf, off eastern Canada. The results of the first year of work are presented here.

The Scotian Shelf is characterized by shallow banks, channels and bays that strongly influence circulation. The complexity of the circulation on all spatial and temporal scales makes this a natural laboratory for the development of data assimilation schemes that are needed to integrate remotely sensed data into coastal ocean models.

The Scotian Shelf modelling effort is being supported by DRDC Atlantic under a Technology Investment Fund project, "Assessment of Underwater Acoustical Environment using Satellite Imagery". The ultimate goal of the work is to develop an operational prognostic model of the Scotian Shelf that could provide ocean data products to the Canadian navy.

A relatively high horizontal resolution of approximately 2 km was selected for the Scotian Shelf model because it is believed to be adequate resolution for modelling range-dependent underwater acoustical propagation.

The model is an implementation of the Princeton Ocean Model (POM) (Ref. 2), a three-dimensional non-linear model that has been used extensively for coastal studies. The prognostic variables of the POM are sea surface elevation, velocity vector, temperature, salinity and turbulent kinetic energy.

Some improvements over the standard POM have been implemented. For example, an improved advection scheme proposed by Smolarkiewicz (Ref. 3) is being used. The advantages of this advection scheme are demonstrated by Pietrezak (Ref. 4). Further extensions to the model are made by allowing time varying open boundary conditions for the momentum and tracer equations and time varying wind and surface pressure fields.

The open boundary conditions for the Scotian Shelf model are provided by nesting it within a lower resolution (1/16 degree) model known as the Dalhousie Coastal Ocean Prediction System (COPS). The COPS has two coupled components; a 2-D non-linear storm surge model and a 3-D POM. Both the storm surge model and the POM are forced by forecasts of high resolution wind and atmospheric pressure from Environment Canada's implementation of the Global Environmental Model (GEM). The storm surge model provides sea-level forcing to the POM which currently provides operational forecasts for the region. The domains of the nested models are shown in Fig. 2.1. Information on COPS and its operational forecasts may be found at www.dal.ca/~dalcoast.

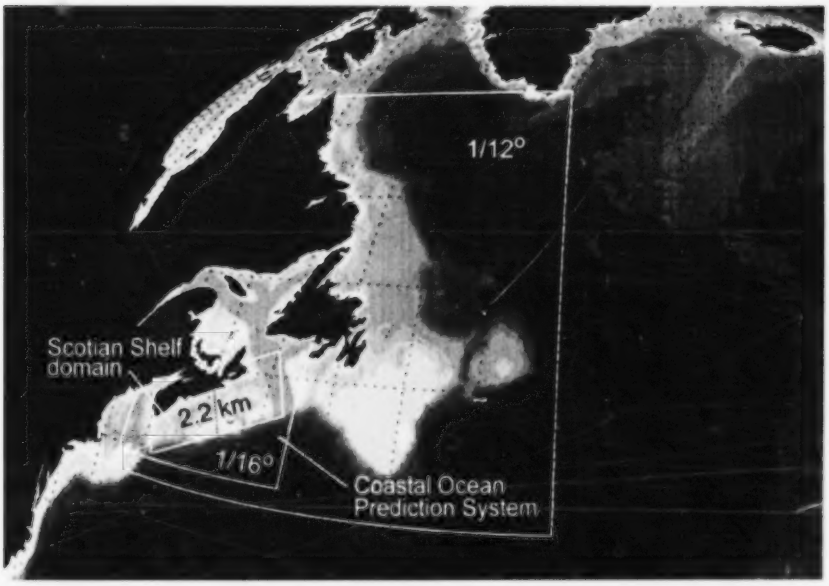

Figure 2.1 Dalhousie University ocean model domains for the Canadian east coast.

The primary goal of the first year of the project was to develop high resolution monthly climatology of temperature and salinity for the Scotian Shelf domain. These climatological fields represent a starting point for the assimilation of temperature or salinity data into the model. The monthly temporal resolution is the best that can be achieved given the available historical data and represents a significant step forward from other climatologies for the area that were only available on seasonal (3-month) time scales and at much coarser spatial resolution.

Two types of data were used to construct the climatology; *in-situ* water column profiles and remotely sensed sea surface temperature (SST). Profile data is derived from direct measurements of temperature and salinity using hydrographic bottles, CTDs and bathythermographs. The data archive, which goes back as far as the year 1910, is vali-

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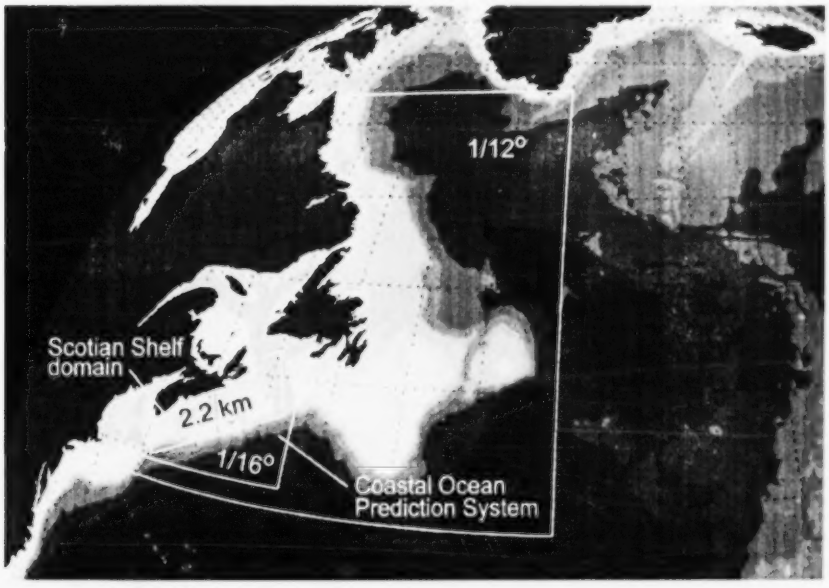

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dated by the Marine Environmental Data Service (MEDS) of the Canadian Department of Fisheries and Oceans (DFO) and was obtained from the Bedford Institute of Oceanography (BIO), in Dartmouth, Nova Scotia. More details on the data archive can be found at http://www.mar.dfo-mpo.gc.ca/science/ocean/database/data-query.html. Examples of the spatial distribution of profile data in winter and summer months are shown in Fig. 2.2.

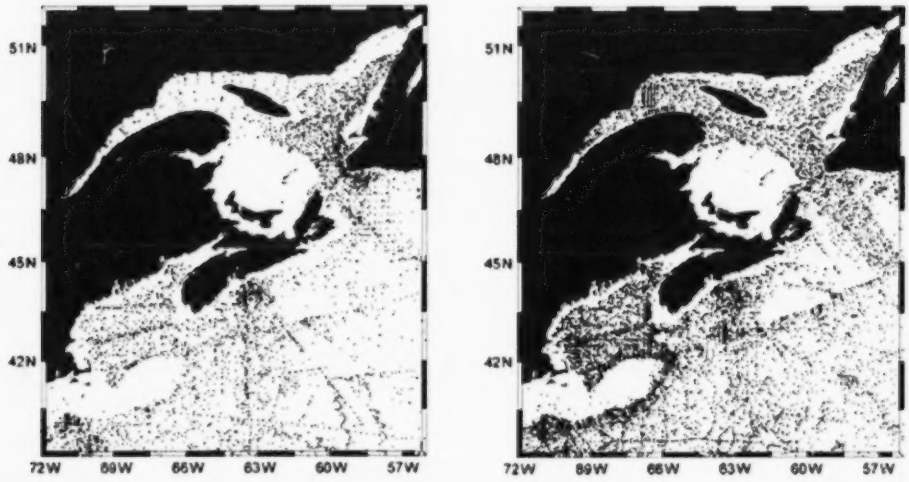


Figure 2.2 Spatial distribution of observed temperature or salinity at 100 m depth, in January (left) and August (right).

Sea surface temperature data were also obtained from BIO, but originated from the Physical Oceanography Archive Centre of NASA's Jet Propulsion Laboratory (JPL) in Pasadena, CA.The SST is from the Advanced Very High Resolution Radiometer (AVHRR) sensors of NOAA's Polar Orbiting Environmental Satellite (POES) family. The SST archive spans the time period from Oct. 1981 to present and has a temporal resolution of 1 week. The spatial resolution is 18 km. Further information on the Physical Oceanography Archive is available at http://podaac-www.jpl.nasa.gov. Examples of SST from this archive are shown in Fig. 2.3.

The amount of available historical data is seasonally dependent for both *in-situ* and remotely sensed data, as can be seen in Figs. 2.2 and 2.3. In the case of *in-situ* data, oceanographic surveys are fewer and military and commercial shipping (which contributes some data) is greatly reduced in the winter months. For remotely sensed SST, it is the prevalence of cloud cover and ice in the winter that inhibits SST coverage.

The monthly climatology based on historical data, was then assimilated into the POM in order to interpolate the data onto the model grid and to generate a set of dynamically balanced monthly fields of temperature and salinity that are consistent with the historical data, and yet conform to dynamical constraints imposed by the model.

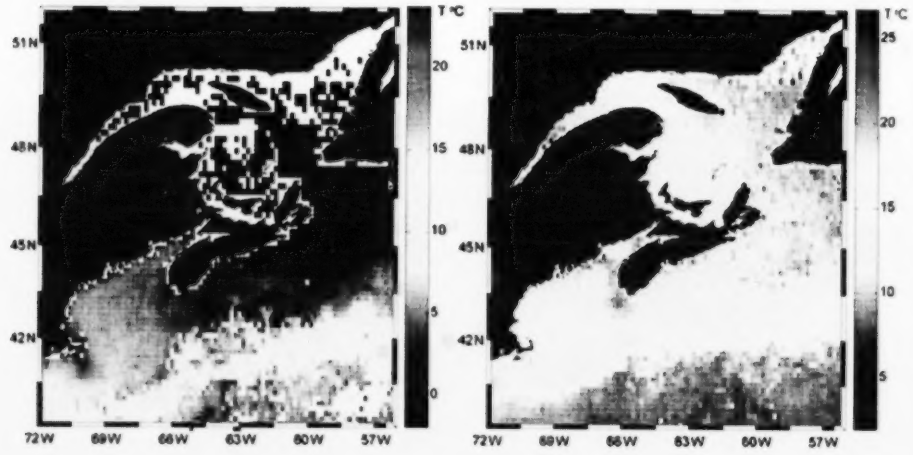


Figure 2.3 A map of weekly averages of sea surface temperature for week 4 (left) and for week 26 (right) based on JPL AVHRR data.

The historical and model climatologies are compared in Fig. 2.4, which shows salinity along a transect through the model domain. The location of the transect is shown by a red dotted line in Fig. 2.1. The agreement between the historical and model fields is good. This is encouraging because near real time salinity data is not expected to be available for assimilation into the model. The only near real time ocean data that has been identified for assimilation into the model is AVHRR SST and the first steps to utilize it are underway. The model climatology now serves as the background for testing the assimilation algorithms.

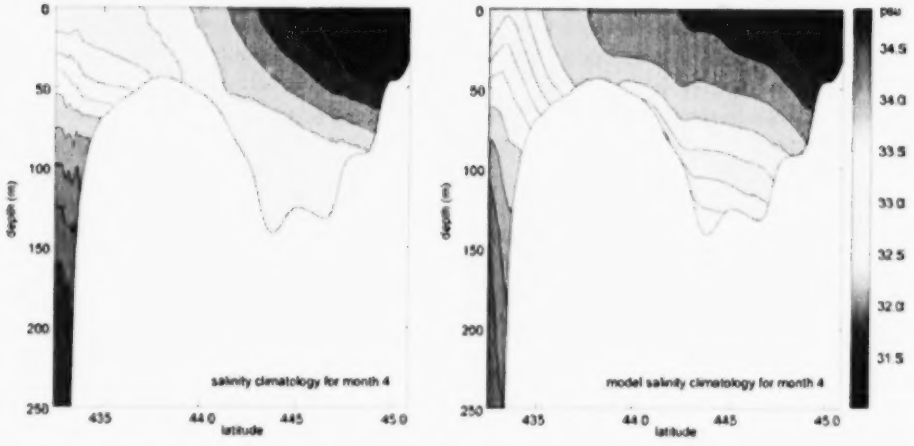


Figure 2.4 Comparison of historical climatology (left) and model climatology (right) for salinity for the month of April. The location of the transect is shown by a red dotted line in Fig. 2.1. The continental slope is on the left side of the images.

2.2 Modular Ocean Data Assimilation System

Charles Barron (Naval Research Laboratory, Stennis Space Center, USA) described the US Navy's Modular Ocean Data Assimilation System (MODAS) which provides the navy with operational estimates of subsurface water parameters on a global scale.

MODAS has a static climatological database which is based primarily on the Master Oceanographic Observation Data Set (MOODS) (Ref. 5). Below depths of 1500 m and in data-sparse areas such as Antarctic ocean, data from Levitus (Refs. 6, 7) is used.

In its dynamic mode of operation, MODAS combines observed ocean data with the static climatology using an optimal interpolation technique to produce a gridded analysis field. Remotely sensed sea surface temperature (SST) and sea surface height (SSH) are combined with in-situ measurements from ships, aircraft or buoys to produce a three-dimensional analysis of the ocean temperature and salinity structure which is consistent with both the surface observations and the static climatology.

The SSH is obtained from the TOPEX/Poseidon and ERS-2 satellite altimeters and the SST is from the AVHRR sensors onboard NOAA polar orbiting satellites. The horizontal resolution of MODAS fields ranges from $1/2^{o}$ in open ocean to $1/8^{o}$ near the coasts. Any *in situ* measurements that are available result in increased accuracy near the site of the measurement.

Comparison of MODAS products with finely sampled water column measurements show significant improvement over profiles estimated on the basis of static climatology. For example, the 2-D temperature profiles from the North Atlantic in Fig. 2.5 show how MODAS predicted the presence of a cold core eddy which was confirmed by a survey of air-deployed expendable bathythermographs (AXBT). Such a feature could not have been predicted on the basis of climatology alone. The dynamic climatology product produced by MODAS represents an extension of traditional static climatologies in that it is able to represent mesoscale synoptic three-dimensional variability of the ocean in response to daily global measurements.

MODAS products are generated daily for the world ocean. The primary data products are three dimensional fields of water temperature, salinity, sound speed, and geostrophic currents. The data is represented by empirical orthogonal functions, compressed using wavelet analysis and output in a naval message format. A full global analysis is approximately 50 Mb in size. The sound speed field component of the MODAS analysis is the basis for a range of navy underwater acoustical applications such as operational sonar performance prediction, vulnerability assessment and tactical decision aids.

MODAS includes a fully relocatable version of the Princeton Ocean Model. The POM obtains boundary conditions from a global implementation of the Navy Coastal Ocean Model, which is constrained by MODAS data. In this way, MODAS provides a mechanism for assimilating remotely sensed and *in situ* data into numerical ocean models. Detailed information on MODAS may be found in Ref. 8 and publicly-available MODAS products may be found at http://www7320.nrlssc.navy.mil/modas/.

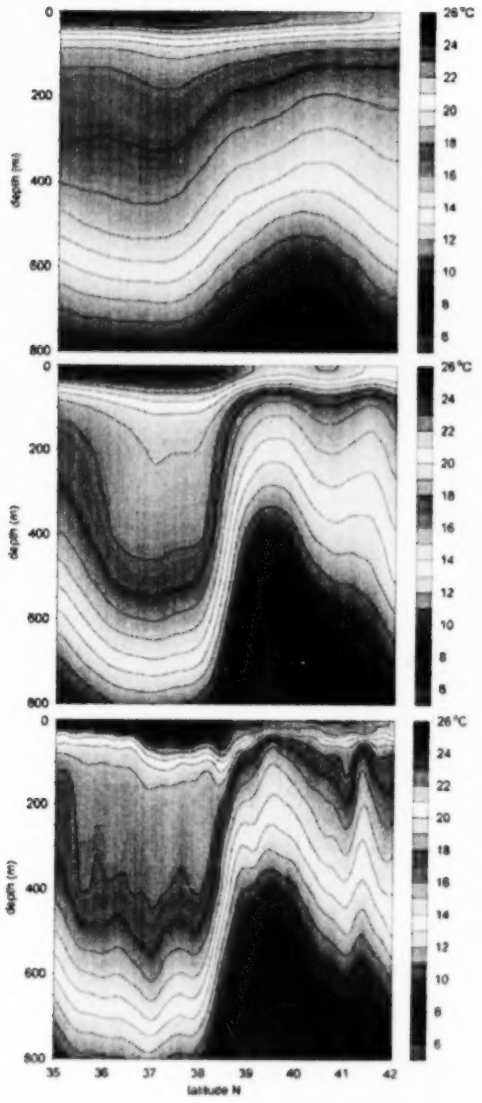


Figure 2.5 Using remotely sensed SST and altimetry, MODAS predicts the presence of a cold-core eddy in the north Atlantic. The top image shows MODAS static temperature climatology, the middle image shows dynamic climatology with the signature of the cold core eddy and the bottom image shows the results of an aircraft bathythermograph survey which confirms the MODAS prediction. The transect is between locations 49.5 W, 35.0 N to 44.8 W, 42.0 N, for Aug. 6, 1995 (image courtesy Charles Barron, NRL SSC).

2.3 Multiscale Environmental Assessment Network Studies

Considering a much finer spatial scale, Henrik Schmidt (MIT, Cambridge, MA) described progress of the Multiscale Environmental Assessment Network Studies (MEANS). MEANS is a cooperative project between MIT, Harvard University's Harvard Ocean Prediction System (HOPS) group and NATO's SACLANTCEN undersea research center. It is aimed at modelling very shallow near-shore regions, with water depths up to only a few tens of meters. Modelling this environment is particularly challenging due to its complex dynamical nature with strong coupling between different spatial scales.

MEANS is a system of nested ocean models. The largest model is the US Navy Coastal Ocean Model (NCOM) basin-scale model of the Mediterranean sea. The NCOM, with a horizontal spatial resolution of approximately 10 km, provides boundary conditions for a 200 km wide regional model of the Ligurian Sea shown in Fig. 2.6. The Ligurian Sea model has a resolution of 2 km and provides the boundary conditions for a very high resolution (0.4 km) model of Procchio Bay on the island of Elba, Italy. The domain of the Procchio Bay model is shown in Fig. 2.7. Both the Procchio Bay and Ligurian Sea models are implementations of the Harvard Ocean Model (Ref. 8).

In September and October, 2000 an experiment known as Generic Oceanographic Array Technology Systems (GOATS) was held in Procchio Bay. The GOATS experiment tested an autonomous ocean sampling network (AOSN) which consisted of fixed moorings and autonomous underwater vehicles (AUV). The network supplied *in situ* ocean data for assimilation into the Procchio Bay model. Benefitting from large quantities of high resolution *in situ* data, the Procchio Bay model was able to output very accurate nowcasts of conditions within its domain.

The MEANS project is demonstrating high accuracy, high resolution prediction of the acoustical environment in the near-shore littoral region in order to improve the performance of AUVs which rely on sonar for navigation and sensing.

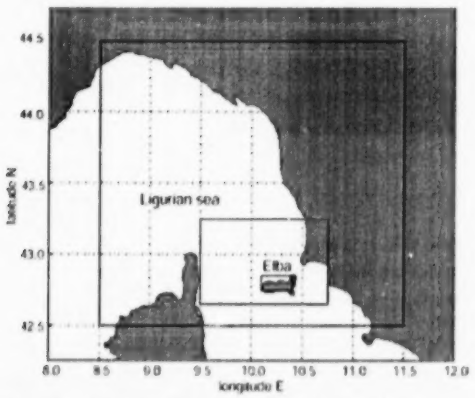


Figure 2.6 Nested computational domains of MEANS Ligurian sea ocean model (graphic courtesy of Henrik Schmidt).

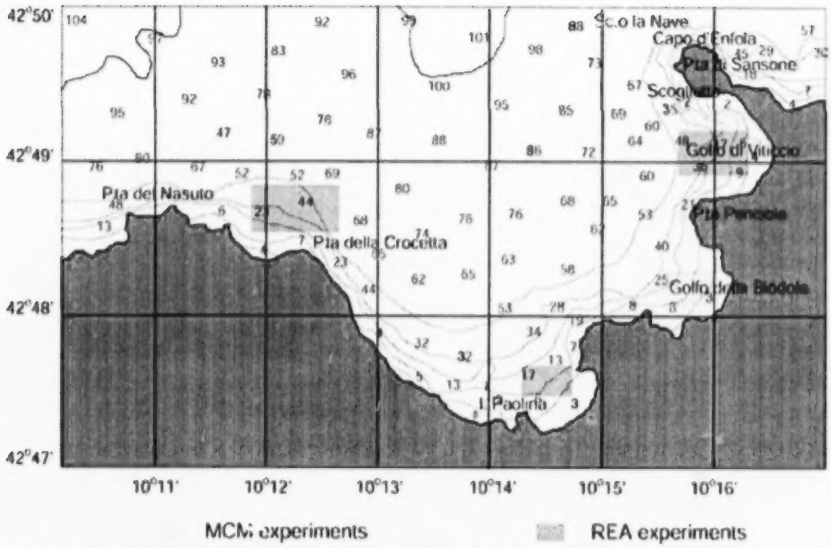


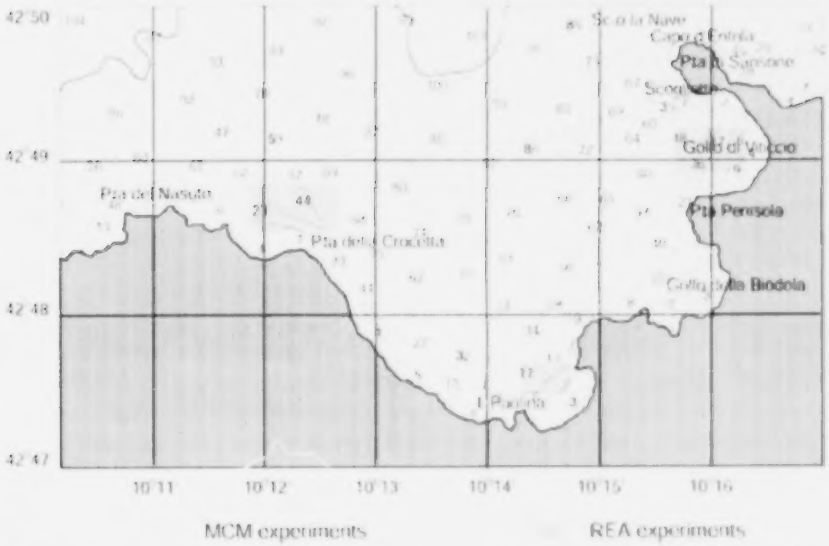
Figure 2.7 High resolution MEANS model domain of Procchio Bay, Elba. GOATS 2000 mine countermeasure (MCM) and rapid environmental assessment (REA) deployment areas are shown (graphic courtesy of Henrik Schmidt).

3. Internal waves

J. Small (University of Hawaii) reported on remote sensing of internal waves using space-based synthetic aperture radar (SAR) imagery and on efforts to model their SAR backscatter signature. Internal waves are slowly propagating sub-surface oscillations of the stratified water column. They are frequently observed at shelf edges in the summer as a result of tidal flow over the bottom topography.

The displacement of the thermocline caused by internal waves can have a great impact on the propagation of underwater sound. If a surface duct is present, internal waves have the potential to disrupt the performance of naval sonar systems by trapping active sonar emissions in regions where the thermocline is made deeper by the internal wave.

Figure 3.1 shows the effect of range-dependent duct depth variation caused by a hypothetical internal wave on cut-off frequency and on leakage at 3 kHz. Horizontal detection ranges for a sonar operating at this frequency would be greatly limited in the direction perpendicular to the internal wave fronts. Propagation of the sonar energy would be constrained to the trough of the internal wave. Thus, internal waves can create a highly azimuthally-dependent propagation environment for sonar. Internal waves can also scatter underwater sound because acoustic modes may be coupled to internal wave modes so that energy is transferred between acoustic modes.



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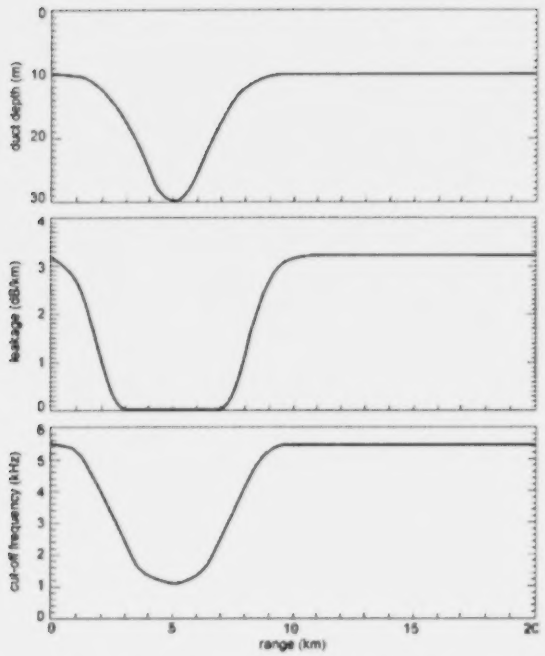

Figure 3.1 Impact of hypothetical internal wave on duct depth (top) on leakage of an acoustic signal of 3 kHz (middle) and acoustic cut-off frequency (bottom) (graphic courtesy of Justin Small).

Figure 3.2 shows a complex internal wave field over the Malin shelf edge north-west of the UK, as seen in ERS-1 SAR imagery. Coincident and near-coincident *in situ* surface current measurements were used to infer the two-dimensional surface current field in the vicinity of the high amplitude internal wave bore enclosed in the red box in the SAR image. The surface current data was used with the C-band backscatter model of Lyzenga and Bennett, Environmental Research Institute of Michigan (Ref. 10) to predict the SAR contrast between the high and low reflectivity bands of the surface of the internal wave. The observed and modeled SAR backscatter contrasts are within 30% of each other. This suggests that it may be feasible to use the remotely sensed SAR backscatter ratio, along with estimates of the width and spacing of internal waves packets, to model the structure of internal waves. Such a capability would be extremely valuable for remote sensing of these important ocean features and for estimating their effect on underwater acoustics (Ref. 11).

Although inversion of internal wave structure from SAR imagery is an alluring prospect, the frequency of space-based SAR imagery is very low. Typically images of the same area are separated by two to three days in mid-latitudes and three to four days near the equator. However many internal wave features are generated by the tides so a tidal recurrence can be assumed to first approximation.

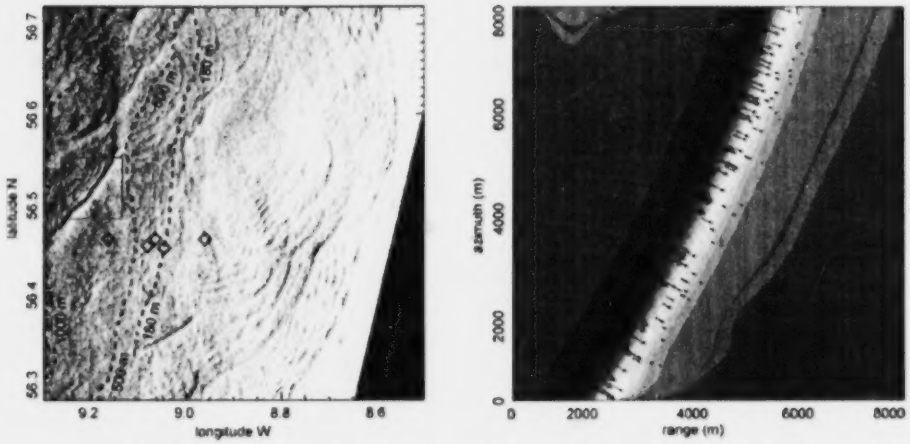

Figure 3.2 ERS-1 SAR image of the Malin shelf-edge, 20th August, 1995 (left) showing a complex internal wave field. Diamond symbols mark the positions of Acoustic Doppler Current Profilers. The red box encloses an internal wave bore for which the relative SAR backscatter was simulated (right) based on the surface currents shown as vectors in the figure (graphics courtesy of Justin Small, ERS-1 image copyright ESA, 1995).

Much work remains in order to exploit the capability for remote sensing of internal waves for assessment of their impact on underwater acoustics. For example, a link must be established between SAR imagery and tidal databases or models in order to take advantage of tidal periodicity. Also, automatic detection and quantification of internal wave signatures in SAR imagery must be improved.

Internal waves should be of concern to the CF as they are prevalent in Canadian continental slope waters, particularly in the late autumn when stratification of the water column is most pronounced. Figure 3.3 shows a RADARSAT-1 image of internal waves in Georgia Strait, British Columbia on the west coast of Canada. Georgia Strait and the Strait of Juan de Fuca are well known for internal wave activity that can be particularly intense due to strong density gradients resulting from the influx of fresh water from major rivers. Farmer and Trevorrow describe observations of internal waves in this part of the world in Refs. 12 and 13.

An example of the structure of an internal wave measured in the Bay of Fundy on Canada's east coast is shown in Fig.3.4. The image shows the intensity of acoustic backscatter measured at 300 kHz with an acoustic Doppler current profiler (ADCP). Variations in backscatter are associated with biogenic and turbulence variations in the water column and trace out changes in the depth of subsurface layers. The bottom-mounted ADCP measured an internal wave soliton as it propagated past the instrument. This internal wave had an amplitude of over 50 m and a wavelength of several hundred meters. It would have had significant impact on the performance of submarine or ship-based sonar operation in its vicinity.

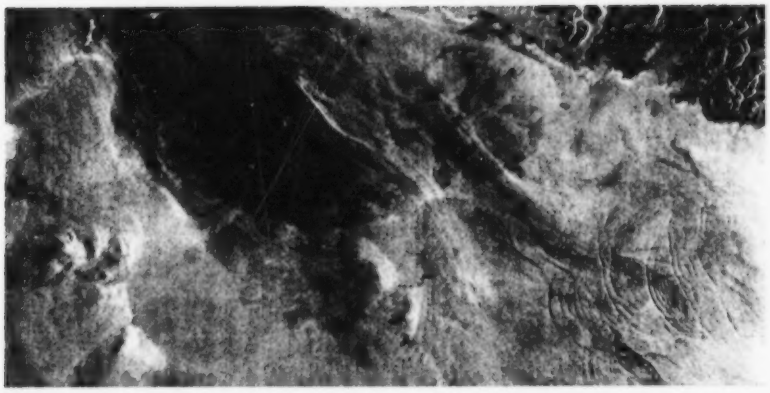

Figure 3.3 RADARSAT-1 Wide swath image of internal waves (lower right corner) in Georgia Strait, British Columbia, Canada (image courtesy Paris Vachon, copyright CSA).

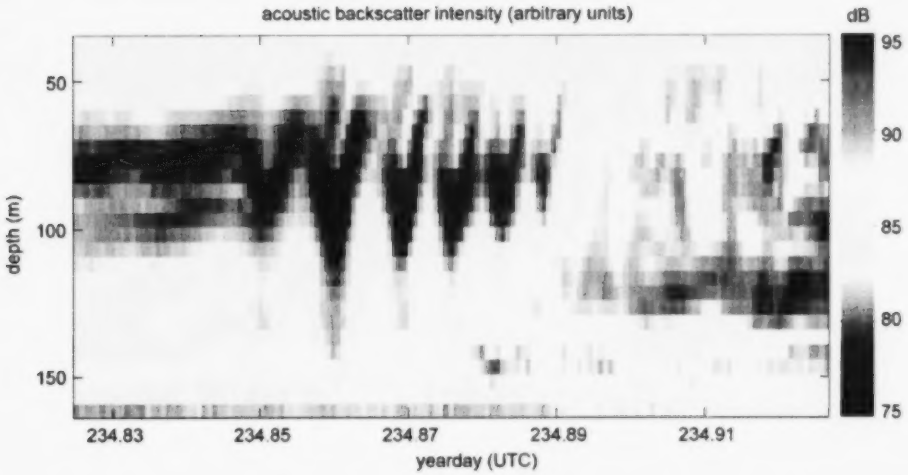

Figure 3.4 Signature of an internal wave measured in the Bay of Fundy, Canada using a bottom-mounted acoustic Doppler current profiler (ADCP). The image shows the intensity of acoustic backscatter measured at 300 kHz. Variations in backscatter are associated with biogenic and turbulence variations in the water column and trace out changes in the depth of subsurface layers. The ADCP measured an internal wave soliton as it propagated past the instrument. This internal wave had an amplitude of over 50 m and a wavelength of several hundred meters.

4. Air-sea interface

Underwater acoustical interaction in the vicinity of the air-sea interface is often a complex mix of scattering by surface roughness, scattering from air bubbles entrained by breaking waves, scattering from fish and Lloyd-mirror boundary interference effects. This interaction can have a significant impact on underwater sound propagation by redirecting and attenuating acoustical energy.

Roger Gauss (Naval Research Laboratory, Washington DC) presented work on models of surface acoustical scattering at frequencies up to 5 kHz that rely on readily observable environmental quantities. The models are based on Bragg scatter from surface waves, and Bragg scatter from sound-speed variations in passively-advecting bubble clouds produced by breaking waves. In addition to bubbles, scatter from fish that may be present near the surface can be significant, particularly at low scattering angles. An example of surface scatter strength measurements is shown in Fig. 4.1.

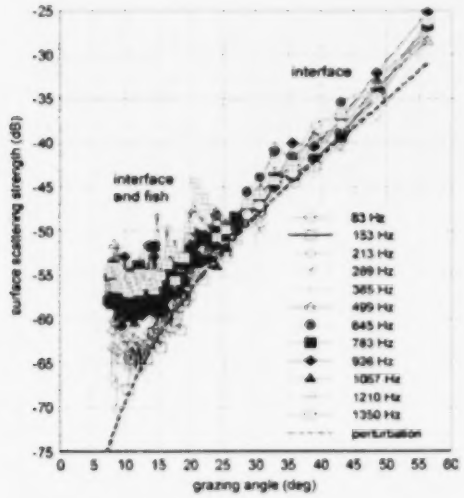

Figure 4.1 Measurements of surface backscattering strength as a function of grazing angle, compared to a perturbation-theory prediction (dashed line) of the interface contribution. The wind speed during these measurements was approximately 5 m/s (graphic courtesy of Roger Gauss, NRL).

While the scattering strength of both surface interface and bubbles can be environmentally parameterized by just the wind speed, bistatic and forward scattering can be sensitive to the details of the surface wave spectrum. Additionally, the mean frequency-shift characteristics of acoustic signals scattered from both the moving sea surface and bubble clouds depend primarily on the two-dimensional (2D) surface wave spectrum. Hence, to characterize acoustic surface scattering, both the wind speed and 2D surface wave spectra need to be estimated on regional scales.

Since Bragg scattering of electromagnetic waves at the sea surface gives rise to the measured backscatter signature in SAR imagery, there is an intimate connection between SAR remote sensing and acoustical scattering by the sea surface. The sensitivity of acoustic surface scattering strength and frequency shifts to environmental variables is such that it may be feasible to use remote sensing to estimate both of these quantities in near real time over wide areas. Estimates of sea surface winds from existing SAR and scatterometer sensors are already adequate and 2D sea surface wave spectra have been measured successfully using airborne SAR. Unfortunately, the quality of remotely sensed surface wave spectra using space-based SAR is still rather poor.

Figure 4.2 shows a comparison between an ocean surface gravity wave spectrum remotely sensed with the RADARSAT-1 SAR sensor and measured simultaneously with a TriAxys wave buoy. While the remotely sensed spectrum reveals the main peak, it lacks detail, and most of the spectrum is below the noise floor of the SAR sensor.

One of the main problems in deriving wave spectra from space-based SAR sensors is the large range-to-velocity ratio which makes the inversion process highly nonlinear and thus inaccurate using current techniques. An even greater difficulty is that the sensitivity of the SAR sensor is restricted to velocity components of the surface wave field that are near-perpendicular to the direction of travel of the satellite, thus limiting the applicability of the technique (Ref. 14).

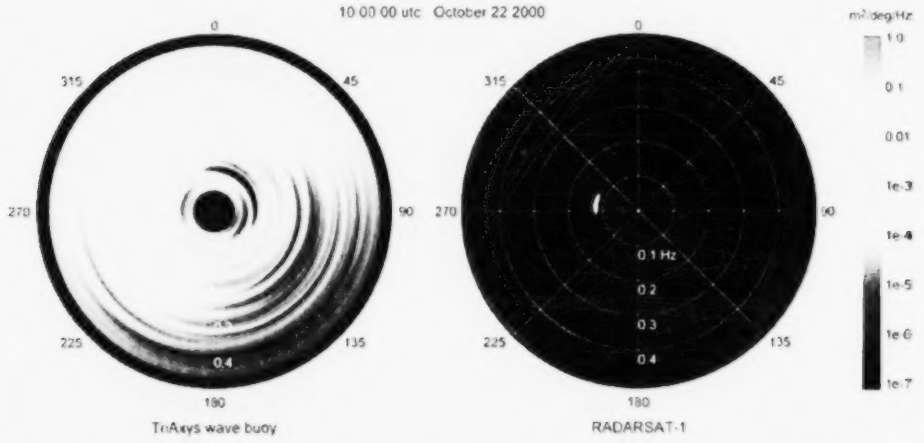

Figure 4.2 Surface gravity wave spectrum measured with a TriAxys wave buoy (left) and same wave field measured with the RADARSAT-1 (right) over the Scotian Shelf, Canada. The remotely sensed spectrum reveals the main peak but lacks detail. (buoy measurement by DRDC Atlantic, SAR processing by Paris Vachon, CCRS).

The NRL model of surface interface scattering (Refs. 15 and 16), based on the small-slope approximation has been shown to work well, but the effects of near-surface bubbles and the unpredictable presence of fish are difficult to quantify. A campaign of broadband, wide -angle acoustic measurements is required to sort out relative contributions of the different scattering mechanisms and to isolate the dependence on environmental parameters.

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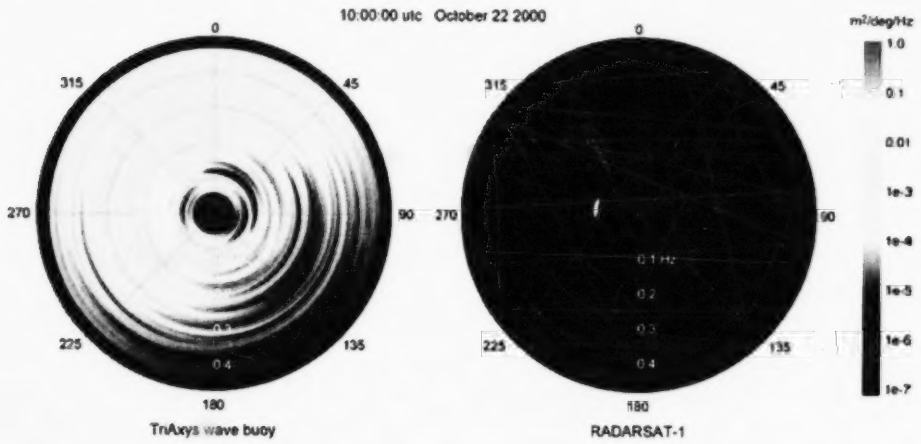

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5. Underwater ambient noise

One of the acoustical parameters required for prediction of sonar performance is the underwater ambient noise field. At frequencies above 10 Hz, underwater ambient noise has two primary sources; shipping noise and environmental noise generated by the turbulent interaction of wind with the sea surface. The noise level at a given location also depends upon water depth, bottom type and propagation conditions since local noise is a superposition of contributions from both nearby and distant sources and is subject to propagation effects.

The author presented work on the estimation of underwater ambient noise with the aid of remotely sensed wind and ship data. Global sea surface wind fields are available daily from the NASA QuickScat scatterometer satellite (www.winds.jpl.nasa.gov). Other scatterometer sensors are the Japanese Spaces Agency's ADEOS (www.eoc.nasda.go.jp) and the European Space Agency's ERS-2 (www.earth.esa.int/ers/instruments/index.html). The revisit time of QuickScat and ADEOS is approximately once per day and for ERS-2 it is approximately once every four days. A visualization of QuickScat data obtained for free from the website above, is shown in Fig. 5.1.

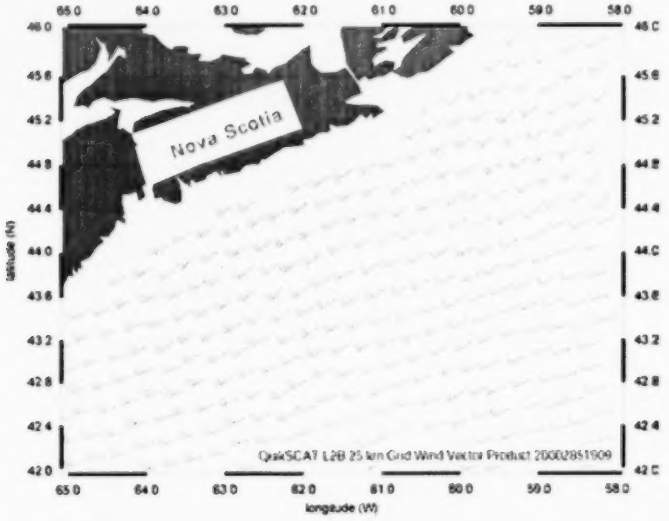

Figure 5.1 Wind field over Scotian shelf from NASA QuickScat satellite, Oct. 11, 2000.

Synthetic aperture radar (SAR) sensors can also provide sea surface wind fields. SAR wind products are typically more accurate than those from scatterometers and can have very high spatial resolutions, up to one to two kilometers. However, space-based SAR wind fields have much smaller spatial coverage, typically 100 km by 100 km as compared to the 1000 km-wide swaths of QuickScat. An example of a wind field derived from a RADARSAT-1 scene is shown in Fig. 5.2. The algorithm of Vachon and Dobson (Ref. 19) was used for the wind retrieval.

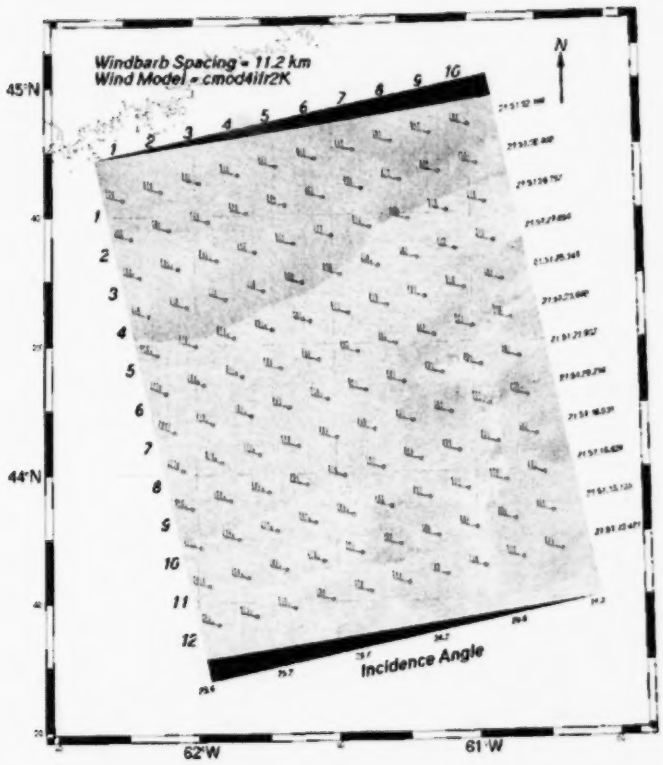

Figure 5.2 Surface wind field over Scotian shelf from CSA RADARSAT-1 satellite, Oct. 11, 2000 (processing by Paris Vachon, CCRS).

In addition to sea surface wind fields, space-based SAR sensors can simultaneously provide ship detections, thus providing the two key quantities required to estimate underwater ambient noise. Space-based SAR has the advantages of being available in all weather, day or night and can provide wide area coverage with swaths up to 500 km across. This availability and coverage gives SAR satellite data the potential to contribute useful information to acoustic environmental assessments for naval applications. Rapid processing and dissemination of SAR data has been demonstrated (Ref. 17) which further strengthens the case for operational use of space-based SAR.

Figure 5.3 shows Canadian Forces research vessel CFAV Quest and its appearance in a RADARSAT-1 standard mode beam 5 SAR image acquired Oct. 21 2000 on the Scotian Shelf (location 44.24N, 61.07W). The length of the Quest is 72 m and it occupies several pixels of the image which has a spatial resolution of approximately 25 m. The turbulent wake of the ship is also visible in the SAR image.

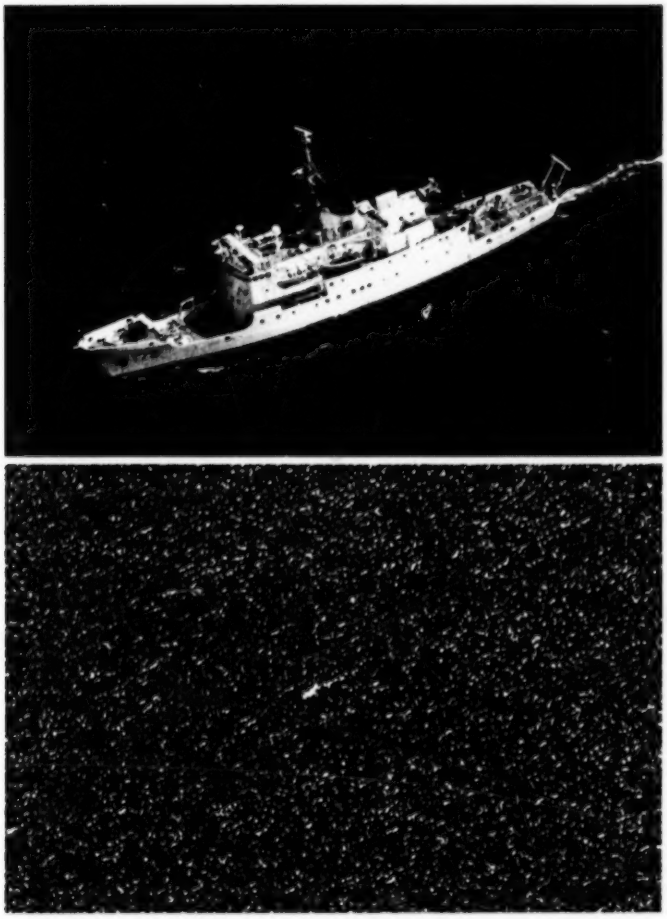

Figure 5.3 Canadian Forces research vessel CFAV Quest (top) and its appearance in a RADARSAT-1 SAR image, Oct. 21 2000, 44.24N, 61.07W, ascending standard mode beam 5 (RADARSAT-1 image copyright CSA).

Automated techniques have been developed to detect ships in SAR imagery. The Ocean Monitoring Workstation (Ref. 17) developed by DRDC Ottawa and Satlantic Inc., Halifax, Nova Scotia, utilizes the constant false alarm rate (CFAR) approach where the image is broken down into many small sub-images whose pixel brightness statistics are compare to the statistics of the whole image. It has been shown to be reliable in detecting ships in the higher standard beams (5,6 and 7) of RADARSAT where the ratio of ship signature to background is greatest (Ref. 18).

A visualization of ship detections from a RADARSAT-1 image using the Ocean Monitoring Workstation (OMW) is shown in Fig. 5.4. The scene was acquired with the standard mode beam 6 on an ascending pass over the Scotian Shelf on Oct. 14, 2000. The research vessel Quest was in the scene at the time of the satellite's overpass. A comparison of targets detected with the Quest's marine radar with OMW ship detections afforded an opportunity to evaluate the OMW's performance. Results of that study are beyond the scope of this report. A target detected by Quest's radar can be seen just north of the ship in Fig. 5.4 but was not detected by the OMW. Other targets to the south of Quest were detected by both Quest's radar and the OMW.

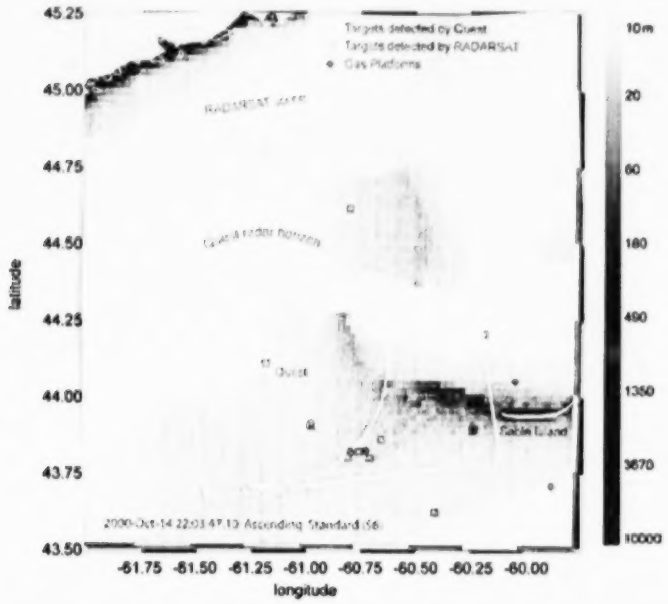

Figure 5.4 Ships detected on the Scotian Shelf using RADARSAT-1 imagery and commercial processing software, Oct. 14, 2000. The research vessel Quest was in the RADARSAT scene at the time of the satellite's overpass. (processing by Paris Vachon, CCRS).

Remotely sensed winds and ship detections can be used as inputs to models to estimate ambient noise levels. On such model is that of Merklinger and Stockhausen (Ref. 20) hereafter referred to as the M&S model. This is an empirical model based on the statistical noise analysis of Wenz (Ref. 21). The inputs for the M&S model are wind speed and a shipping density parameter. An example of an underwater ambient noise spectrum predicted using the M&S model is shown in Fig. 5.5 where the contributions of wind and ship noise components can be seen.

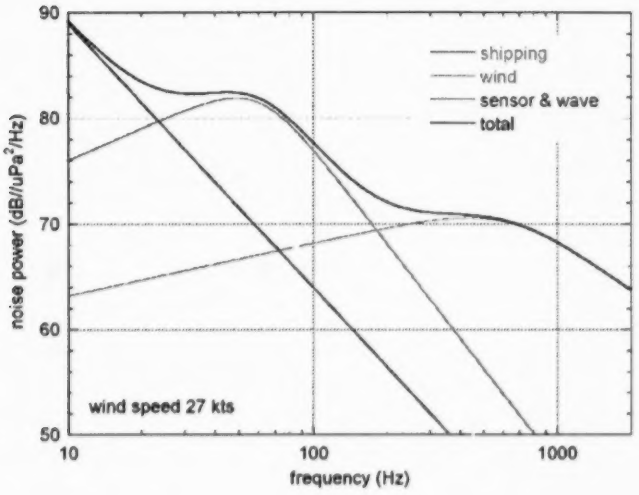

Figure 5.5 Example of underwater ambient noise prediction using Merklinger and Stockhausen model showing contributions of wind and ship noise components.

Although acoustical propagation effects and seabed interaction are not taken into account in the M&S model, an adjustment of 3 dB can added to the wind-generated component of the model when used for shallow water areas, according to Piggott (Ref. 22). This adjustment accounts for the overall higher noise levels at frequencies above 200 Hz usually experienced in shallow water as a result of sea bed interaction.

More sophisticated models for underwater ambient noise are available such as RANDI (Ref. 23) and CANARY (Ref. 24) which take into account the details of ship location and estimated size, information which is available from SAR imagery. However, results obtained with the M&S model are sufficient to demonstrate the concept of using remotely sensed environmental data to estimate ambient noise. Also, results from this simple model are much better than those obtained from data bases of historical ambient noise levels which are still widely used.

An analysis of the sensitivity of ambient noise to wind speed showed that the accuracy of remotely sensed surface wind using RADARSAT-1 and ERS-2 SAR is adequate for ambient noise predictions in the 100 Hz to 1000 Hz band (Ref. 25). In one experiment carried out near Bermuda it was found that winds derived from standard mode RADARSAT-1 imagery yielded ambient noise estimates with the M&S model that were within 1 dB of the measured values. These results were for acoustical frequencies above 200 Hz where wind noise dominates and for deep water (> 1000 m) where the M&S model is valid. A comparison between a measured ambient noise power spectrum from the Bermuda experiment and the output of the M&S model is shown in Fig. 5.6.

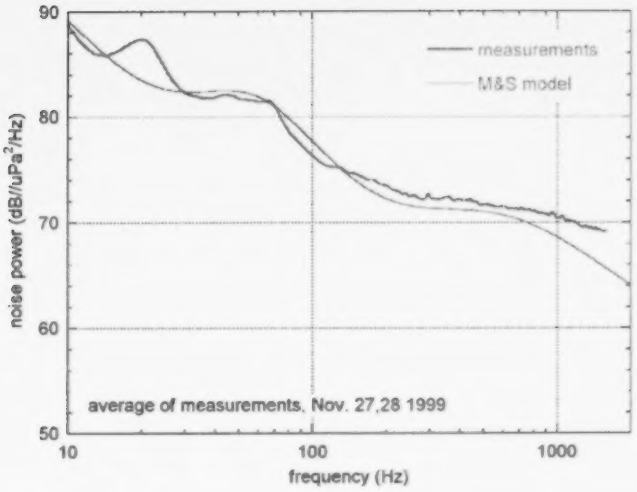

Figure 5.6 Comparison of underwater ambient noise measured in deep water off Bermuda and prediction based on windspeed measured with RADARSAT-1.

In today's security environment, littoral or shallow water regions are of greater interest and pose a much greater modelling challenge. Sophiscated ambient noise models will have to be employed and information on the geoacoustic environment and water sound speed conditions will be required in order to predict ambient noise on the basis of remotely sensed winds and ships.

It should be pointed out that the accuracy of SAR wind and ship data products are complementary to the requirements of ambient noise modelling. This is because ship detection accuracy improves as wind speed decreases and the relative accuracy of SAR wind estimates increases as wind speed increases. This is exactly what is required for predicting ambient noise - accurate ship data during low-wind conditions when ship noise dominates and accurate wind speeds when wind noise is dominant.

6. Summary

The work presented at this session fell into two broad categories: modelling of ocean structure with the aid of assimilated remotely sensed data and direct interpretation of remotely sensed surface characteristics. Since the speed of sound in water is primarily a function of water temperature (with a lesser dependence on salinity and depth) the output of oceanographic models can be readily interpreted in terms of acoustical propagation.

The availability of global operational remote sensing data such as provided by the AVHRR sensors and radar altimeters has allowed ocean models to operate at scales ranging from the littoral zone to global. It was apparent from the session that much work remains to be done to fully exploit the information content of remotely sensed data. The steadily increasing coverage and resolution of remote sensing products coupled with advances in computation and modelling techniques holds tremendous potential for nowcasting and forecasting the acoustical ocean environment.

The temporal and spatial frequencies of internal waves are too great for these ocean features to be resolved by finite-difference primitive equation models such as the Princeton or Harvard Ocean Models. Therefore monitoring and modelling of internal waves is closely linked to high-resolution satellite remote sensing. Synthetic Aperture Radar is particularly sensitive to the modulation of surface roughness caused by internal waves and is therefore an ideal method to detect them. It was shown that internal waves can have a significant impact on underwater acoustical propagation and hence on sonar performance. With internal waves occurring in many areas off the coasts of Canada, detecting, modelling and predicting these ocean features should be of importance to the Canadian navy.

It was shown that there is good potential for estimating acoustical scattering strength at the sea surface using wind data provided by space based SAR. While the scattering strength of both surface interface and bubbles can be environmentally parameterized by just the wind speed, bistatic and forward scattering can be sensitive to the details of the surface wave spectrum.The wave spectrum is a quantity that is not well measured by existing remote sensing technologies.

Combining remotely sensed winds with ship detections enables the underwater ambient noise field to be estimated. However the narrow swath widths, between 100 and 500 km, and long repeat times of approximately two to three days preclude its use operationally. Improved wind and ship detection anticipated from the next generation of polarimetric SAR satellites may translate into even better ambient noise estimates. However, for shallow water applications, information about the geoacoustic properties of the sea bed must be taken into account in order to predict ambient noise in this environment.

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